AD-A134 482   ION IMPLANTATION IN POLYMERS(U) NAVAL ACADEMY ANNAPOLIS   1/1
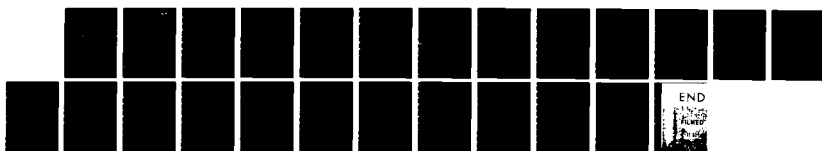   MD DEPT OF PHYSICS M C WINTERSGILL ET AL. AUG 83 TR-9
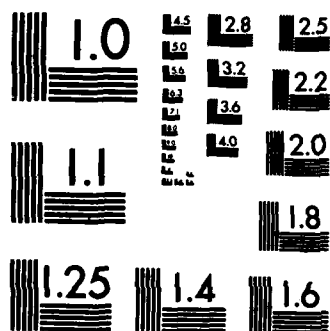   N00014-83-AF-00001
UNCLASSIFIED   F/G 7/4   NL

END
FILMED

MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

OFFICE OF NAVAL RESEARCH

Contract N00014-83-AF-00001

Task No. NR 627-793

TECHNICAL REPORT NO. 9

ION IMPLANTATION IN POLYMERS

by

Mary C. Wintersgill & John J. Fontanella

Prepared for Publication

in

Proceedings of the 2nd International Conference
on Radiation Effects in Insulators to be
published as a special issue of "Nuclear
Instruments & Methods in Physics Research."

U. S. Naval Academy
Department of Physics
Annapolis, MD 21402

DTIC
SELECTE
NOV 8 1983
D

August 1983

DTIC FILE COPY

83 11 07 017

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER $11'9$	2. GOVT ACCESSION NO. $AD-A134$ $Y FL$	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ION IMPLANTATION IN POLYMERS		5. TYPE OF REPORT & PERIOD COVERED Interim Technical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) MARY C. WINTERSGILL & JOHN FONTANELLA		8. CONTRACT OR GRANT NUMBER(s) N0001483AF00001
9. PERFORMING ORGANIZATION NAME AND ADDRESS Physics Department U. S. Naval Academy Annapolis, MD 21402		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR No. 627-793
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Attn: Code 413, 800 N. Quincy St. Arlington, VA 22217		12. REPORT DATE August 1983
		13. NUMBER OF PAGES 14
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release and sale.
Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Polymers, ion inplantation, radiation, polymer electrolytes, photoresists, polyethylene, polyacetylene, poly(p phenylene sulfide), conductivity

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An introductory overview will be given of the effects of ion implantation on polymers, and certain areas will be examined in more detail. Radiation effects in general and ion implantation in particular, in the field of polymers, present a number of contrasts with those in ionic crystals. The most obvious difference being that the chemical effects of both the implanted species and the energy transfer to the host may profoundly change the nature of the target material. Common effects →

DD $_{1 JAN 73}^{FORM}$ 1473 EDITION OF 1 NOV 68 IS OBSOLETE
S/N 0102-014-6601 |

include crosslinking and scission of polymer chains, gas evolution, double bond formation and the formation of additional free radicals.

Research has spanned the chemical proces.. involved, including polymerization reactions achievable only with the use of radiation, to applied research dealing both with the effects of radiation on polymers already in commercial use and the tailoring of new materials to specific applications. Polymers are commonly divided into two groups, in describing their behavior under irradiation. Group I includes materials which form crosslinks between molecules, whereas Group II materials tend to degrade. In basic research, interest has centered on Group I materials and of these polyethylene has been studied most intensively. Applied materials research has investigated a variety of polymers, particularly those used in cable insulation, and those utilized in ion beam lithography of etch masks. Currently there is also great interest in enhancing the conducting properties of polymers, and these uses would tend to involve the doping capabilities of ion implantion, rather than the energy deposition.

ION IMPLANTATION IN POLYMERS*

M. C. Wintersgill
Physics Department
U. S. Naval Academy
Annapolis, MD 21402

An introductory overview will be given of the effects
of ion implantation on polymers, and certain areas will be
examined in more detail. Radiation effects in general and
ion implantation in particular, in the field of polymers,
present a number of contrasts with those in ionic crystals.
The most obvious difference being that the chemical effects
of both the implanted species and the energy transfer to
the host may profoundly change the nature of the target
material. Common effects include crosslinking and scission
of polymer chains, gas evolution, double bo:' formation and
the formation of additional free radicals.

Research has spanned the chemical processes involved,
including polymerization reactions achievable only with the
use of radiation, to applied research dealing both with the
effects of radiation on polymers already in commercial use and
the tailoring of new materials to specific applications.
Polymers are commonly divided into two groups, in describing
their behavior under irradiation. Group I includes materials
which form crosslinks between molecules, whereas Group II
materials tend to degrade. In basic research, interest has
centered on Group I materials and of these polyethylene has
been studied most intensively. Applied materials research
has investigated a variety of polymers, particularly those
used in cable insulation, and those utilized in ion beam
lithography of etch masks. Currently there is also great
interest in enhancing the conducting properties of polymers,
and these uses would tend to involve the doping capabilities
of ion implantation, rather than the energy deposition.

Accession For	
NTIS GRA&I	X
DTIC TAB	☐
Unannounced	☐
Justification	

By_____

Distribution/

Availability Codes

Dist	Avail and/or Special

A/l

1

1. Introduction

The purpose of this paper is to introduce the topic of ion implantation in polymers using the perspective of ionic crystals. The scheme of this paper will be a simple introduction of the basic concepts prevalent in polymer studies, followed by a discussion of some of the typical effects of ion implantation and radiation energy deposition in general, with some illustrative examples drawn from recent literature. Many generalizations and a somewhat arbitrary choice of examples are made in the interests of clarity and brevity.

2. Introduction to Polymer Physics:

In general, polymers may be grouped according to their physical properties; thermosetting-, rubber-and thermoplastic-type polymers. Of these, thermoplastic polymers have found the most numerous applications and attracted the most research interest. This type of polymer commonly exists in three phases, listed in order of increasing disorder; glassy, rubbery and viscofluid. The glassy state is characterized by vibrational motion of individual atoms or small segments of the macromolecule. As the temperature of the polymer is increased, the glass transition occurs (Tg) as a distinct endothermic event when intense thermal motion of molecular segments becomes dominant. Increasing temperature can cause a second transition to occur at a point sometimes called the flow temperature, when large scale thermal motion of large parts of the macromolecule becomes characteristic. However, it is not always well defined and in some significant cases - e.g. poly(ethylene oxide), there is merely a monotonic decrease in viscosity as temp increases. An alternative morphology seen most commonly in simple linear molecules is the existence of a crystalline phase, which undergoes melting to the appropriate amorphous state at some well defined melting temperature, Tm.

2

The crystalline phase has stimulated a lot of interest and it is possible in a few cases, notably polydiacetylene, to produce large single crystals (cm dimensions). This is commonly achieved by solid state polymerization, often using ionizing radiation to affect the polymerization (see, for example "Introduction to Polymers" by R. J. Young, [1] Ch. 2.). It is far more common, however, for polycrystalline material to coexist with the appropriate amorphous phase, and the degree of crystallinity of a sample is an important parameter in determining many of the physical properties of these polymers. In such cases, the crystalline regions are often lamellar in structure and the lamellae frequently occur in some form of spherulitic morphology. Since, in a large number of cases, the macromolecules are very "long" in comparison with the thickness of individual lamellae, considerable folding of the molecules occurs. The region surrounding the "folds" in the molecules appears to be more reactive and is involved in the growth of the crystal lamellae under certain circumstances. In addition to these configurational variations, the macromolecular chains have an internal conformation, of which the planar zig zag (e.g. polyethylene) and the helix (e.g. poly(ethylene oxide)) are two which are of particular current interest.

3. Introduction to Implantation Effects.

Having given a brief summary of the structure and morphology to be expected in polymeric materials, it is instructive to consider the effect of the deposition of energy into such systems. Until recently, the damage produced by ion implantation seems to have been the effect of primary interest, however some recent work which also makes use of the doping capabilities of implantation will be mentioned later. The dominant effect of energy deposition is the creation of free radicals, which are, of course, highly reactive. Taking polyethylene as an example, [2], this means that a single neutral hydrogen atom and a free radical carbon are created. Both of these species may be involved in a variety of reac-

3

tions which typically include crosslinking or scission of the polymer chain, gas evolution and double bond formation e.g. $CH_2 - CH_2 \rightarrow CH = CH + H_2$.

The evolution of gases of various types, some with relatively complex molecules can be used in various ways. Work by Venkatesan et al [3] suggests a convenient technique for measuring the very low diffusion coefficients ($D < 10^{-10}$ cm^2/s) of some of the larger gas molecules evolved during in ion beam irradiation (e.g. various deuterated formic, acetic and propionic acids in PMMA.) A number of theories have been developed in the chemical literature regarding the exact details of the many possible reactions. w. a regard to the probability of crosslinking vs chain scission it has been stated as a general rule that simple unbranched chains will tend to crosslink, whereas similar molecules having large side groups or extensive branching will tend to degrade. As is usually the case, a number of examples contradicting this generalization may easily be quoted.

Changes in susceptibility to oxidation have also been noted in implanted polymers. In considering the polymer during implantation, there is an increased susceptibility to oxidation associated with the presence of sufficient energy in conjunction with the reacting species [4]. Studies of radiation enhanced oxidation have been caried out in, for example, polyethylene [5,6], poly(ethylene oxide) [7] and poly(vinyl chloride) [8,9]. However, once the implantation is complete, there is evidence that some materials, polyacetylene for example, show an enhanced resistance to surface oxidation in the atmosphere [10]. In conjunction with the chemical effects, there are a number of physical properties which have been of interest to researchers and a few of those dealt with recently in the literature will serve as examples.

4. Applications of Ion Implantation.

In a large number of cases the degree of crystallinity is changed substantially by irradiation. In the case of polymers which form crosslinks under

4

irradiation there is in general an increase in the degree of crystallinity. In the case of polyethylene the crosslinking occurs preferentially in the amorphous phase, however Bhateja et al [11,12] show some rather interesting results of γ-irradiating ultra high molecular weight (U.H.M.W.) polyethylene. In the case of such very long molecules, there are significant numbers of tie molecules which tend to inhibit crystallization. γ-irradiation preferentially breaks the tie molecules, allowing small scale reorganization among the chains, resulting both in an increase in the perfection of existing crystallites and a growth of additional lamellae. Kusy and Turner [13] report another aspect of crosslinkage formation, in this case in poly(ethylene oxide), namely the depression of the melting point of the crystalline material. The depression, measured by differential thermal analysis, was found to be 0.15 K/Mrad and is attributed to the effective removal of crosslinked units from the equilibrium between crystalline and amorphous material, whose temperature dependence defines the melting temperature.

Another effect attributable largely to the formation of crosslinks is that on the tensile properties of materials. Bhateja and Andrews [14] again working on U.H.M.W. polyethylene noted about a 15% increase in tensile yield stress after 120 MRad of 2 MeV electrons. In addition, the creep strain was observed to be reduced by a factor of five after 64 MRad, which is probably due largely to crosslinking in the amorphous phase, since degree of crystallinity had little effect on this result.

Another physical property which undergoes changes upon irradiation largely because of crosslinking or scission is the solubility, leading to a number of applications in the field of resist materials. In a number of resist materials, both positive and negative resists, the exposure of the resist scales roughly linearly with the linear energy transfer (LET) of the ionizing radiation.

5

Studies of positive resists such as PMMA [15 ‚‾], Komuro et al, MacIver), PMMA

plus copolymers like PVA [15], and negative resists such as poly(dimethy/siloxane)

[16] and polystrene [15] all show an exhanced exposure rate and excellent reso-

lution [17]. For most positive resists, the exposure mechanism simply involves

the scission of the molecular chains resulting in an increased solubility. Of

the negative resists, which become less soluble as a result of crosslinking, some

actually undergo crosslinking via simultaneous activation of sites on two adja-

cent chains. In these cases exposure is additionally enhanced by the high energy

density surrounding the track of an implanted ion.

Finally, the conducting properties of polymers have become of immense impor-

tance as their advantages as solid state electrolytes have become apparent.

Both electron- and ion-conducting polymers have been investigated and studies of

ion implantation into electron-conductors have shown an enhancement of conduc-

tivity as a result of damage formation and because of reactions with the

implanted species.

In the realm of high energy, high dose implantations, the work of Venkatesan

et al [18-20] is representative. In this work, doses of 10^{16}-10^{17}cm^{-2} of 2 MeV Ar

ions were implanted into PMMA, PVC, a polyimide and some commercial resist materials.

Under such conditions there is substantial loss of the target materials, with a

decrease to about 50% of the initial film thickness. At doses between 10^{14} and

5×10^{15}cm^{-2} the conductivity of the polymers is shown to increase approximately

linearly with dose, over 12 orders of magnitude and saturate at a dose of about

10^{16}cm^{-2}. This behavior appears to be a general characteristic of a large number

of polymer and "organic" materials [21,22]. After implantation of 10^{16} –

10^{17} cm^{-2} Ar ions, Raman spectra indicate that the material is highly disordered

with evidence of the existence of crystallites similar to amorphous carbon. The

temperature dependence of the conductivity seems to follow an $\exp[T^{-1/2}]$ function.

6

rather that the exp $[T^{-1/4}]$ seen in amorphous semiconductors and comparison is drawn with the work by Sheng & Abeles [23,24] on hopping conduction in metal grains dispersed in an insulating medium. It appears, therefore that at such high doses and energies the effects are largely due to damage effects in graphitized polymers, whose original structure is largely irrelevant.

Similar results have been seen by Mazurek et al [25,26] in poly(p-phenylene sulphide) bombarded with 100 KeV ^{75}As and ^{84}Kr. However, they also include a careful characterization of the samples after bombardment as well as the results of chemical doping implantations using 100 KeV ^{80}Br ... Poly(p-phenylene sulphide) doped with AsF$_5$ is known to have useful electron-conducting properties, in addition to some processing advantages, despite the fact that the conductivity is unstable in a moist atmosphere. Chemical doping with bromine is also known to enhance the electron conducting properties of a number of polymers and the purpose of the experiments was to see if similar chemical effects could be produced by ion implantation. Instead of the more conventional four probe conductivity measurements, which can be unreliable when applied to thin films, the more elegant technique of spin casting the polymer film over a planar interdigitated electrode structure was used. Current vs voltage curves for the As and Br implantations show ohmic behavior up to about 5 volts, above which space charge effects are observed. Again, the conductivity increases up to about 10^{15} cm^{-2}. No appreciable difference is observed between the Kr, producing damage only, and the As which might be supposed in interact chemically with the polymer. However, the implanted films did shown an enormously improved resistance to degradation in air. Perhaps surprisingly, the Br implanted samples do indeed show evidence of chemical activity, having consistently higher conductivities after doses of 10^{16}cm^{-2} [Fig. 1] The temperature dependence of the conductivity for both Kr and Br implanted samples show interesting behavior,

7

having a discontinuity at 150K [Fig.2]. Such behavior has not been observed in any chemically doped samples. Both sections of the Kr curve and the lower temperature portion of the Br curve indicate a thermally activated conduction mechanism, however the high temperature portion of the Br curve is fitted to a $\ln\sigma = BT^{-m}$ giving a value of m in the range 0.2-0.6. This latte may indicate that a variable range hopping mechanism becomes dominant about   K. Infrared studies of the As and Kr implanted samples indicated extensive c   slinking in the polymer but little chemical bonding of the implanted specie.   le Auger spectroscopy indicates some sulfur depletion in the   'ace layers. In this work, the possibility of the enhanced conductivity being due to the carbon rich surface layer was eliminated by removal of that layer and a subsequent measurement of the same bulk conductivity. Other work by this group [26] using other halogen ions, shows a consistent enhancement of electronic conductivity, which appears to scale approximately with the electronegativity of the species, once the damage induced conductivity effect has reached saturation. In all cases the discontinuity in σ as a function of temperature occured at 150K suggesting some type of implantation induced phase transition.

The work by Weber et al [10,29-29] concentrates on the chemical doping effects of ion implantation, thus far dealing with a number of halogen ions and various "inert" ions implanted into polyacetylene at energies from 10-40 KeV and doses up to 10^{18} cm^2. XPS (ESCA) investigations show that the halogens occupy a single type of site, bonded to the polymer backbone. NMR studies of ^{19}F implanted polyacetylene [29] indicate that esentially all the implanted ions remain within the target and that the chlorine nuclei are well dispersed through the polymer. It is again noted that the normally rather unstable polyacetylene samples showed a marked resistance to decomposition in air. Similar studies of fluorine and carbon tetrafluoride (1 KeV) implanted into polyacetylene, polybuta-

8

diene and polystyrene by Rabalais et al [30] using XPS also show that the fluorine ions bond chemically to the polymer backbone. Both -CHF- and -CF$_2$-environments are produced, regardless of the precise form of the bombarding ion or the exact nature of the target polymer. Again, the implanted films were resistant to degradation in air, and indeed, a small XPS peak from oxygen contamination was almost eliminated during irradiation.

In summary, then, there are a remarkably large variety of phenomena related to ion implantation into polymers. The convenience and processability of polymers coupled with the enormous variety of materials available, have already lead to extensive use in almost all industrial fields. Probable applications of implanation techniques are already apparent in for example, mask technology and development of polymer electrolytes. The effects both of damage formation and of chemical modification are sources of intensely interesting work and highly promising applied research.

References

[1] R. J. Young "Introduction to Polymers" Chapman E. Hall, London, (1981).

[2] G. Ungar, J. Mat. Sci., 16 (1981) 2635

[3] T. Venkatesan, D. Edelson, W. L. Brown, Appl. Phys. Lett. submitted.

[4] T. Fujimura, N. Hayakawa, I. Kuriyama, J. Appl. Poly Sci, 27 (1982) 4093

[5] K. Arakawa, T. Seguchi, Y. Watanabe, N. Hayakawa, I. Kuriyama, S. Machi, J. Poly. Sci: Poly. Chem. Ed. 19 (1981) 2123.

[6] K. Arakawa, T. Seguchi, Y. Watanabe, N. Hayakawa, J. Poly. Sci.: Poly. Chem. Ed. 20 (1982) 2681.

[7] C. Decker, J. Poly. Sci.: Poly Chem. Ed. 15 (1979) 799

[8] C. Decker, J. Appl. Poly Sci. 20 (1976) 3321

[9] E. A. Hegazy, T. Seguchi, S. Machi, J. Appl. Poly. Sci. 26 (1981) 2947

[10] D. C. Weber, P. Brant, C. A. Carosella, Metastable Materials Formation by Ion Implantation: Eds. S. T. Picraux and W. J. Choyke, Elsevier Science, 1982.

[11] S. K. Bhateja, J. Macromol. Sci-Phys. B22 (1983) 159

[12] S. K. Bhateja, E. H. Andrews, R. J. Young, J. Poly Sci: Poly. Phys. Ed. 21 (1983) 523.

[13] R. P. Kusy, D. T. Turner, Macromol 10 (1977) 493.

[14] S. K. Bhateja, E. H. Andrews, Polymer 24 (1983) 160.

[15] T. M. Hall, A. Wagner, L. F. Thompson, J. Appl. Phys. 53 (1982) 3997.

[16] M. Komuro, N. Atoda, H. Kawakatsu, J. Electrochem Soc: Solid State Sci. & Tech. 126 (1979) 483

[17] B. A. MacIver, J. Electrochem. Soc: Solid State Sci. & Tech 129 (1982) 827

[18] T. Venkatesan, S. R. Forrest, M. L. Kaplan, C. A. Murray, P. H. Schmidt, B. J. Wilkens, J. Appl. Phys. to be published.

[19] T. Venkatesan, W. L. Brown, C. A. Murray, K. J. Marcantonio, B. J. Wilkens. Poly. Eng. Sci. to be published.

[20] B. Wilkens, T. Venkatesan, this conference.

[21] S. R. Forrest, M. L. Kaplan, P. H. Schmidt, T. Venatesan, A. J. Lovinger, Appl. Phys. Lett. 41 (1982) 708

Figure Captions

Figure 1. Log-log plot of mean conductivity-fluence characteristics of 0.2-μm thick PPS films implanted with bromine ions. The mean conductivity-fluence data for krypton-implanted PPS films are shown for comparison. (Ref. 25)

Figure 2. Log of the mean conductivity vs. reciprocal temperature for bromine- and krypton-implanted PPS films. These data have been interpreted in terms of a $\sigma \sim \exp(-T^{-m})$ functional form. The discontinuity of each curve suggests a phase transition in the PPS host and corresponds to a temperature of about 150 K. (Ref. 25)

[22] A. J. Lovinger, S. R. Forrest, M. L. Kaj... , P. H. Schmidt, T. Venkatesan, J. Appl. Phys. submitted.

[23] P. Sheng, B. Abeles, Y. Arie, Phys. Rev. Lett. 31 (1973) 44

[24] B. Abeles, P. Sheng, M. D. Coutts, Y. Arie, Adv. in Phys. 24 (1975) 407

[25] H. Mazurek, D. R. Day, E. W. Maby, J. S. Abel, S. D. Senturia, M. S. Dresselhaus, G. Dresselhaus. J. Poly Sci: Poly. Phys. Ed. 21 (1983) 537.

[26] J. S. Abel, H. Mazurek, D. R. Day, E. W. Maby, S. D. Senturia, G. Dresselhaus, M. S. Dresselhaus. p.173, Metastable Materials Formation by Ion Implantation, Eds. S. T. Picraux and W. J. Choyke. Elsevier Sci. 1982.

[27] D. C. Weber, P. Brant, C. Carosella, L. G. Banks, J. Chem. Soc: Chem. Comm. (1981) 522.

[28] W. N. Allen, P. Brant, C. A. Carosella, J. J. DeCorpo, C. T. Ewing, F. E. Saalfield, D. C. Weber, Synth. Metals, 1 (1979/80) 151.

[29] L. G. Banks, H. A. Resing, D. C. Weber, C. Carosella, G. R. Miller, P. Brant, J. Phys. Chem. Sol. 43 (1982) 351.

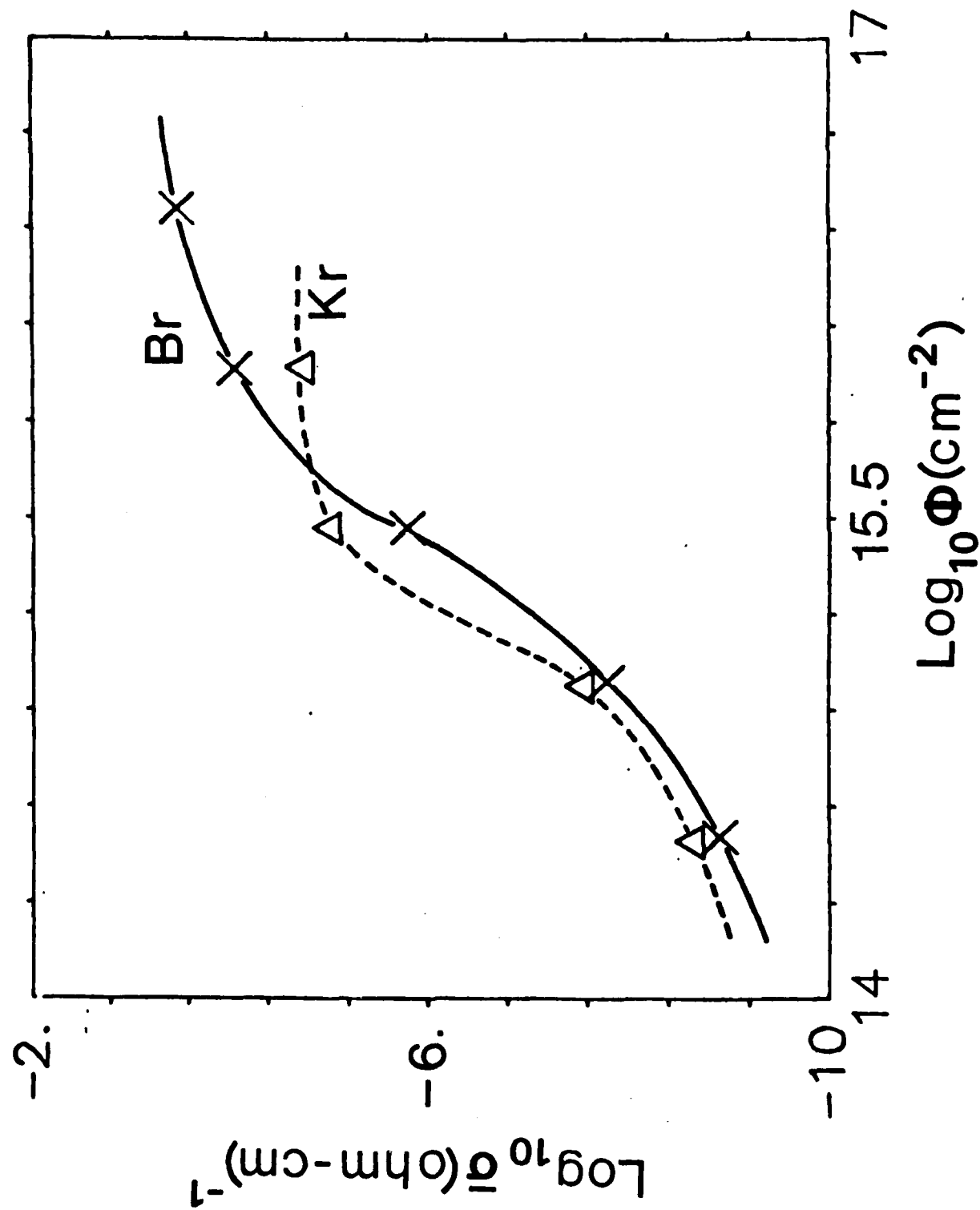[30] H. K. Hu, J. A. Schultz, J. W. Rabalais, J. Phys. Chem. 86 (1982) 3364.
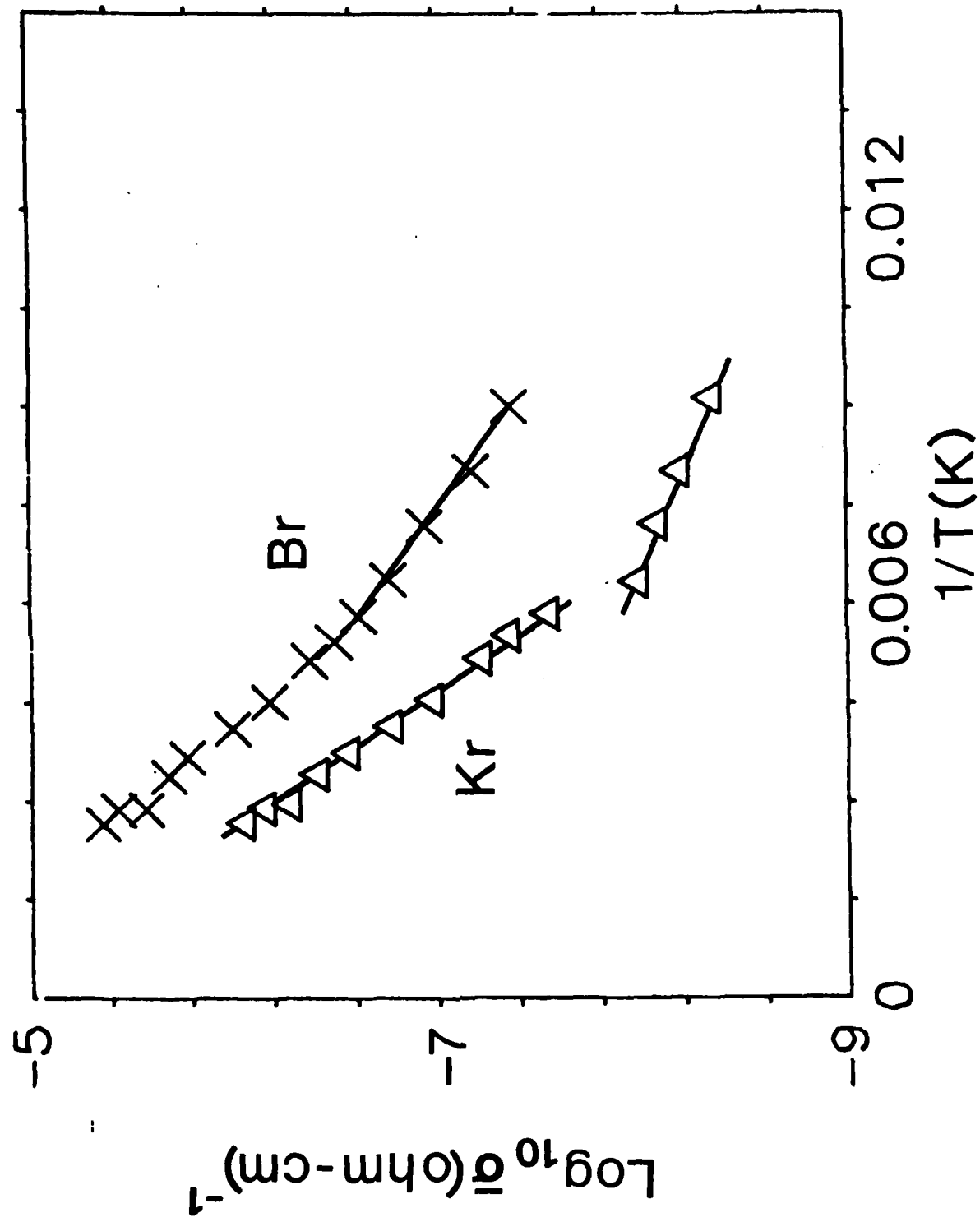
11

Figure 1

13

Figure 2

14

TECHNICAL REPORT DISTRIBUTION LIST, GEN

	No. Copies		No. Copie:
Office of Naval Research Attn: Code 413 800 North Quincy Street Arlington, Virginia 22217	2	Naval Ocean Systems Center Attn: Mr. Joe McCartney San Diego, California 92152	1
ONR Pasadena Detachment Attn: Dr. R. J. Marcus 1030 East Green Street Pasadena, California 91106	1	Naval Weapons Center Attn: Dr. A. B. Amster, Chemistry Division China Lake, California 93555	1
Commander, Naval Air Systems Command Attn: Code 310C (H. Rosenwasser) Department of the Navy Washington, D.C. 20360	1	Naval Civil Engineering Laboratory Attn: Dr. R. W. Drisko Port Hueneme, California 93401	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22314	12	Dean William Tolles Naval Postgraduate School Monterey, California 93940	1
Dr. Fred Saalfeld Chemistry Division, Code 6100 Naval Research Laboratory Washington, D.C. 20375	1	Scientific Advisor Commandant of the Marine Corps (Code RD-1) Washington, D.C. 20380	1
U.S. Army Research Office Attn: CRD-AA-IP P. O. Box 12211 Research Triangle Park, N.C. 27709	1	Naval Ship Research and Development Center Attn: Dr. G. Bosmajian, Applied Chemistry Division Annapolis, Maryland 21401	1
Mr. Vincent Schaper DTNSRDC Code 2803 Annapolis, Maryland 21402	1	Mr. John Boyle Materials Branch Naval Ship Engineering Center Philadelphia, Pennsylvania 19112	1
Naval Ocean Systems Center Attn: Dr. S. Yamamoto Marine Sciences Division San Diego, California 91232	1	Mr. A. M. Anzalone Administrative Librarian PLASTEC/ARRADCOM Bldg 3401 Dover, New Jersey 07801	1

TECHNICAL REPORT DISTRIBUTION LIST, 359

	No. Copies		No. Copies

Dr. Paul Delahay
Department of Chemistry
New York University
New York, New York 10003 — 1

Dr. E. Yeager
Department of Chemistry
Case Western Reserve University
Cleveland, Ohio 41106 — 1

Dr. D. N. Bennion
Department of Chemical Engineering
Brigham Young University
Provo, Utah 84602 — 1

Dr. R. A. Marcus
Department of Chemistry
California Institute of Technology
Pasadena, California 91125 — 1

Dr. J. J. Auborn
Bell Laboratories
Murray Hill, New Jersey 07974 — 1

Dr. Adam Heller
Bell Laboratories
Murray Hill, New Jersey 07974 — 1

Dr. T. Katan
Lockheed Missiles and
  Space Co., Inc.
P. O. Box 504
Sunnyvale, California 94088 — 1

Dr. Joseph Singer, Code 302-1
NASA-Lewis
21000 Brookpark Road
Cleveland, Ohio 44135 — 1

Dr. B. Brummer
EIC Incorporated
55 Chapel Street
Newton, Massachusetts 02158 — 1

Library
P. R. Mallory and Company, Inc.
Northwest Industrial Park
Burlington, Massachusetts 01803 — 1

Dr. P. J. Hendra
Department of Chemistry
University of Southampton
Southampton SO0 5NH
United Kingdom — 1

Dr. Sam Perone
Chemistry & Materials
  Science Department
Laurence Livermore National Lab.
Livermore, California 94550 — 1

Dr. Royce W. Murray
Department of Chemistry
University of North Carolina
Chapel Hill, North Carolina 27514 — 1

Naval Ocean Systems Center
Attn: Technical Library
San Diego, California 92152 — 1

Dr. C. E. Mueller
The Electrochemistry Branch
Materials Division, Research and
  Technology Department
Naval Surface Weapons Center
White Oak Laboratory
Silver Spring, Maryland 20910 — 1

Dr. G. Goodman
Johnson Controls
5757 North Green Bay Avenue
Milwaukee, Wisconsin 53201 — 1

Dr. J. Boechler
Electrochimica Corporation
Attn: Technical Library
2485 Charleston Road
Mountain View, California 94040 — 1

Dr. P. P. Schmidt
Department of Chemistry
Oakland University
Rochester, Michigan 48063 — 1

TECHNICAL REPORT DISTRIBUTION LIST, 359

	No. Copies		No. Copies
Dr. H. Richtol Chemistry Department Rensselaer Polytechnic Institute Troy, New York 12181	1	Dr. R. P. Van Duyne Department of Chemistry Northwestern University Evanston, Illinois 60201	1
Dr. A. B. Ellis Chemistry Department University of Wisconsin Madison, Wisconsin 53706	1	Dr. B. Stanley Pons Department of Chemistry University of Alberta Edmonton, Alberta CANADA T6G 2G2	1
Dr. M. Wrighton Chemistry Department Massachusetts Institute of Technology Cambridge, Massachusetts 02139		Dr. Michael J. Weaver Department of Chemistry Michigan State University East Lansing, Michigan 48824	1
Larry E. Plew Naval Weapons Support Center Code 30736, Building 2906 Crane, Indiana 47522	1	Dr. R. David Rauh EIC Corporation 55 Chapel Street Newton, Massachusetts 02158	1
S. Ruby DOE (STOR) 600 E Street Providence, Rhode Island 02192	1	Dr. J. David Margerum Research Laboratories Division Hughes Aircraft Company 3011 Malibu Canyon Road Malibu, California 90265	1
Dr. Aaron Wold Brown University Department of Chemistry Providence, Rhode Island 02192	1	Dr. Martin Fleischmann Department of Chemistry University of Southampton Southampton 509 5NH England	1
Dr. R. C. Chudacek McGraw-Edison Company Edison Battery Division Post Office Box 28 Bloomfield, New Jersey 07003	1	Dr. Janet Osteryoung Department of Chemistry State University of New York at Buffalo Buffalo, New York 14214	1
Dr. A. J. Bard University of Texas Department of Chemistry Austin, Texas 78712	1	Dr. R. A. Osteryoung Department of Chemistry State University of New York at Buffalo Buffalo, New York 14214	1
Dr. M. M. Nicholson Electronics Research Center Rockwell International 3370 Miraloma Avenue Anaheim, California	1		

TECHNICAL REPORT DISTRIBUTION LIST, 359

	No. Copies		No. Copies
Dr. Donald W. Ernst Naval Surface Weapons Center Code R-33 White Oak Laboratory Silver Spring, Maryland 20910	1	Mr. James R. Moden Naval Underwater Systems Center Code 3632 Newport, Rhode Island 02840	1
Dr. R. Nowak Naval Research Laboratory Code 6130 Washington, D.C. 20375	1	Dr. Bernard Spielvogel U. S. Army Research Office P. O. Box 12211 Research Triangle Park, NC 27709	1
Dr. John F. Houlihan Shenango Valley Campus Pennsylvania State University Sharon, Pennsylvania 16146	1	Dr. Denton Elliott Air Force Office of Scientific Research Bolling AFB Washington, D.C. 20332	1
Dr. D. F. Shriver Department of Chemistry Northwestern University Evanston, Illinois 60201	1	Dr. David Aikens Chemistry Department Rensselaer Polytechnic Institute Troy, New York 12181	1
Dr. D. H. Whitmore Department of Materials Science Northwestern University Evanston, Illinois 60201	1	Dr. A. P. B. Lever Chemistry Department York University Downsview, Ontario M3J1P3 Canada	1
Dr. Alan Bewick Department of Chemistry The University Southampton, S09 5NH England		Dr. Stanislaw Szpak Naval Ocean Systems Center Code 6343 San Diego, California 95152	1
Dr. A. Himy NAVSEA-5433 NC #4 2541 Jefferson Davis Highway Arlington, Virginia 20362		Dr. Gregory Farrington Department of Materials Science and Engineering University of Pennsylvania Philadelphia, Pennsylvania 19104	
Dr. John Kincaid Department of the Navy Strategic Systems Project Office Room 901 Washington, D.C. 20376		Dr. Bruce Dunn Department of Engineering & Applied Science University of California Los Angeles, California 90024	

TECHNICAL REPORT DISTRIBUTION LIST, 359

	No. Copies		No. Copies

M. L. Robertson
Manager, Electrochemical
  and Power Sonices Division
Naval Weapons Support Center
Crane, Indiana 47522 — 1

Dr. Elton Cairns
Energy & Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720 — 1

Dr. Micha Tomkiewicz
Department of Physics
Brooklyn College
Brooklyn, New York 11210 — 1

Dr. Lesser Blum
Department of Physics
University of Puerto Rico
Rio Piedras, Puerto Rico 00931 — 1

Dr. Joseph Gordon, II
IBM Corporation
K33/281
5600 Cottle Road
San Jose, California 95193 — 1

Dr. Robert Somoano
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103 — 1

Dr. Johann A. Joebstl
USA Mobility Equipment R&D Command
DRDME-EC
Fort Belvior, Virginia 22060 — 1

Dr. Judith H. Ambrus
NASA Headquarters
M.S. RTS-6
Washington, D.C. 20546 — 1

Dr. Albert R. Landgrebe
U.S. Department of Energy
M.S. 6B025 Forrestal Building
Washington, D.C. 20595 — 1

Dr. T. Marks
Department of Chemistry
Northwestern University
Evanston, Illinois 60201 — 1

Dr. D. Cipris
Allied Corporation
P. O. Box 3000R
Morristown, New Jersey 07960 — 1

Dr. M. Philpot
IBM Corporation
5600 Cottle Road
San Jose, California 95193 — 1

Dr. Donald Sandstrom
Washington State University
Department of Physics
Pullman, Washington 99164 — 1

Dr. Carl Kannewurf
Northwestern University
Department of Electrical Engineering
  and Computer Science
Evanston, Illinois 60201 — 1

Dr. Edward Fletcher
University of Minnesota
Department of Mechanical Engineering
Minneapolis, Minnesota 55455 — 1

Dr. John Fontanella
U.S. Naval Academy
Department of Physics
Annapolis, Maryland 21402 — 1

Dr. Martha Greenblatt
Rutgers University
Department of Chemistry
New Brunswick, New Jersey 08903 — 1

Dr. John Wassib
Kings Mountain Specialties
P. O. Box 1173
Kings Mountain, North Carolina 28086 — 1

TECHNICAL REPORT DISTRIBUTION LIST, 359

	No. Copies		No. Copies
Dr. J. J. Brophy University of Utah Department of Physics Salt Lake City, Utah 84112	1		
Dr. Walter Roth Department of Physics State University of New York Albany, New York 12222	1		
Dr. Thomas Davis National Bureau of Standards Polymer Science and Standards Division Washington, D.C. 20234	1		
Dr. Charles Martin Department of Chemistry Texas A&M University	1		
Dr. Anthony Sammells Institute of Gas Technology 3424 South State Street Chicago, Illinois 60616	1		
Dr. H. Tachikawa Department of Chemistry Jackson State University Jackson, Mississippi 39217	1		
Dr. W. M. Risen Department of Chemistry Brown University Providence, Rhode Island	1		